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Final Report

Research Report

Concept Development of a Solid and Semi-Solid Manure Injector

Hubert Landry, P.Eng., Ph.D.
Project Leader

Philip Leduc, P.Eng., B.E.
Senior Manager
Research and Development

Signature on File

Acknowledgement

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1. Summary

Solid and semi-solid organic fertilizers (i.e. manures, composts, sludges) are generally broadcast applied to the surface of agricultural lands to be recycled by soil-crops systems. However, liquid organic fertilizers are usually injected under the soil surface. There are several advantages to applying organic fertilizers directly under the soil surface. Among those benefits is the minimization of nutrient losses as runoff and by emission to the atmosphere, as well as, the reduction of greenhouse gas and odour emissions. The technology currently available for the land application of solid organic fertilizers does not allow for subsurface application.

The objective of this project was therefore to develop a solid manure injection device. The injection device was divided into two subsystems: a manure conveying subsystem and a soil-engaging subsystem. Two main concepts were investigated to fulfill the conveying function, namely mechanical conveying and extrusion. Mechanical conveying by a flexible screw conveyor featuring a steel cable as its core gave the most satisfactory performance in terms of discharge rate and power requirements. Two concepts of soil-engaging tools were studied. A plough (mouldboard) was tested with the objective of achieving a system that lifts the soil to allow for manure deposition and then drops the soil back. A disc opener was also investigated. The large diameter disc performed well and opened a trench of satisfactory depth and width. The disc also showed a level of soil (and residue) disturbance that was deemed much more appropriate than the plough.

A single injector device was assembled to prove the concept of solid manure injection. The flexible screw conveyor and disc opener concepts were successfully combined to perform solid manure injection at a typical 1-year rate for beef cattle manure (feedlot manure).

2. Objective

The objective of this project was to develop a working concept of a solid manure injector to prove that injection of solid organic fertilizers is a realistic goal.

3. Project Description

The project was divided into several steps. During the development of the precision land applicator at the University of Saskatchewan, the research team made a number of observations leading to the conclusion that processing of the manure may be desirable, if not required, in order to achieve solid manure injection.

The initial step of the current project was, therefore, to investigate processing systems. The evaluation of two types of manure processors is reported in Section 5.

The second step was for the team to evaluate the prototype precision manure applicator developed at the University of Saskatchewan that was to be the basis of the current project. There is a direct relationship between the output of the injection device and the manure land applicator in terms of mechanical design. It was therefore important for the team members to assess the performance of the prototype land applicator (Section 6).

The third step of the project was to design the conveying subsystem of the injection device; that is, the subsystem whose function it is to transport the product from the land applicator to the ground. This step is detailed in Section 7.

As the conveying subsystem was developed, soil-opening systems were evaluated. This task, although not as challenging as the development of the conveying subsystem, demanded nevertheless the careful selection of a system capable of opening a trench of satisfactory volume while maintaining an acceptable level of soil disturbance. The development of the soil-engaging subsystem is presented in Section 8.

Finally, the conveying and soil-engaging subsystems had to be integrated to meet the objective of the current project. The concept of solid manure injection was proven as being viable as presented in Section 9.

4. Literature Review

The literature review required within the scope of the current project is related to the conveying subsystem of the injection device. The injection of solid and semi-solid manure requires the conveying or transport of these products over a given distance and at a given rate.

4.1 Pumps

Due to the obvious complexity and uniqueness of the problem of solid manure injection, several technological avenues had to be investigated. One of the first steps was to meet with Dr. Randy Gillies of the Saskatchewan Research Council's (SRC) Pipe Flow Technology Center. SRC has a vast experience of pumping non-Newtonian fluids. Discussions were focused on the type of technology capable of moving solid and semi-solid products. SRC's expertise is mostly related to fluid products (as opposed to solid and semi-solid) and pumping. The Moyno pump (http://www.moyno.com) was identified as a potential means of conveying manure in an injection system. With a unique rotor design, the Moyno pump is allegedly capable of handling a variety of hard-to-pump fluids. However, the progressive cavity pump action creates cavities that progress from the suction to the discharge end of the pump. That pumping action was deemed impractical for solid products. Moreover, the cost of such a pump is prohibitive for an application such as manure injection. Several other types of pumps were investigated. Piston pumps, such as the ones used in the concrete industry, have been looked at. These pumps are capable of moving fluids like concrete, but the suction part of the pump action was again raising concerns for solid products. The peristaltic hose pump works on the principle of alternatively contracting and relaxing the hose forcing the content through the pump and into the discharge piping. The hose restitution after compression creates a vacuum that draws the product into the hose from the intake piping. Pumping allows the system to move the product to the discharge point without the presence of mechanical parts at that discharge point. However, feeding a pump with a solid product presents difficulties. Moreover, most pumps used with manure or wastewater sludge are limited to 15% solids. Common drawbacks of all types of pumps include technical complexity, high cost, and difficulty in feeding the pump.

4.2 Mechanical Conveyors

Mechanical conveyors have also been considered as they have the capability of positively displacing the product from the inlet to the outlet of the system. However, the concept of a solid manure injector requires the conveyor to reach under the soil surface, unless gravity is part of the system. For practical application rates to be possible, a machine that involves gravity requires travel speeds that were deemed unacceptable.

With such restrictions, the choice of mechanical conveyors becomes limited. The flexible screw conveyor features characteristics that match the requirements of the manure injector. It is basically a steel coil that rotates inside a tube or a hose.

4.3 Extrusion

The extrusion process consists in pushing or thrusting a product out. It is generally used to form a product by forcing it through a die. Several types of extruders are used in a variety of industries. The three main types of extruders are the rotary extruders, the ram extruders, and the screw extruders (Benbow and Bridgwater, 1993). The optimization of the design and operation of an extruder is a complex task that requires taking into account a large number of parameters. As with pumping, extrusion does not require mechanical parts all the way to the discharge point of the system. Extruding over long distances (10 to 15 ft (3 to 4.6 m)) is however perceived as a major challenge.

Interesting features were highlighted by the literature review on extrusion systems. Stasi et al. (1983) reported on longitudinal stator bars to prevent rotation of the product in the extruder barrel. Also, the proposed screw extruder offers the option of adjusting the position of the screw relative to the barrel. A change in compression ratio can therefore be achieved by moving the extruder screw relative to the tapered section of the barrel. Stasi et al. (1983) also mentioned that the addition of water to the biomass may be required for optimal operation of the extruder.

Hamilton (2003) also proposed an extruder featuring longitudinal ribs to prevent the product from rotating with the screw conveyor. When in operation, the screw conveyor is supported by the annulus of moving compacted product that acts as a bearing.

4.4 Other Technological Options

As mentioned, an obvious option to bring the manure from the machine to the ground was the use of gravity. However, the targeted application rates ruled out gravity feeding. Pneumatic conveying has also been considered. It has been successfully applied to seeding applications. The complexity of a pneumatic system for solid manure handling was however deemed prohibitive.

5. Manure Processing

As an upstream function to the injection device, manure processing was investigated. The objectives of this preliminary assessment were to: (1) evaluate the ability of the processors to break down the clumps and make the products more homogeneous in terms of particle size, (2) measure the effect of processing on bulk density, and (3) measure the power requirements of the processors.

5.1 Materials and Methods

5.1.1 Processor Test Benches

Two test benches were tested. The first one was built for a previous project with the objective of chopping carrots. It is based upon the straw chopper of a combine. It features knives rigidly mounted on a cylinder and fixed counter knives (**Figure 1**). The second test bench was built from the straw chopper of a John Deere pull-type combine. The chopping mechanism consists of fixed counter knives and rotating flails mounted on a shaft (**Figure 2**). Both units were PTO driven.

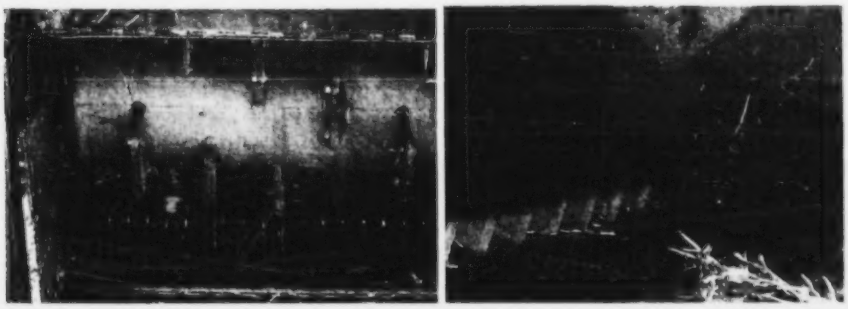

Figure 1. Knife Chopper.

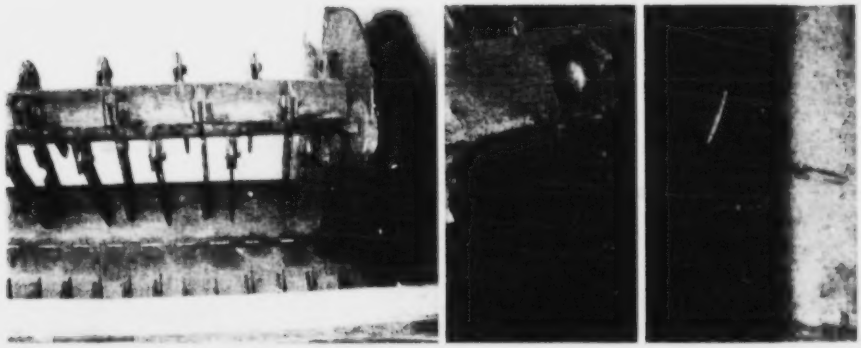

Figure 2. Flail Chopper.

5.1.2 Feedlot Manure Samples

Three types of manure were used. Two 45-gallon barrels of each manure type were collected to allow for a direct comparison of the two processor concepts. A first sample of composting beef cattle manure was collected. This sample was light and dry. A second sample of fresh beef cattle manure was used. This second sample had a paste-like consistency and was much heavier than the first one. Finally, a sample was collected from a feedlot pen. This last sample contained a large amount of straw.

5.1.3 Density Measurements

The bulk density of the products was measured before and after processing. The density was measured by weighing large containers of known volume filled with manure, according to the method described by Glancey and Hoffman (1996).

5.1.4 Moisture Content Measurements

Three subsamples of each manure types were oven-dried for 24 hours at 103°C. The wet and dry weights were used to calculate the moisture content (ASAE Standards, 2002).

5.1.5 Power Requirements

A PTO torque transducer was used along with a magnetic speed sensor to determine the power required by the processors. The manure samples were placed in the bucket of a front-end loader and dropped in the processors (**Figure 3**). The feedrate was not accurately controlled during this preliminary assessment.

5.1.6 Assessment of Processing Capabilities

The processing capabilities of both processors in terms of particle size reduction and homogenization were visually assessed.

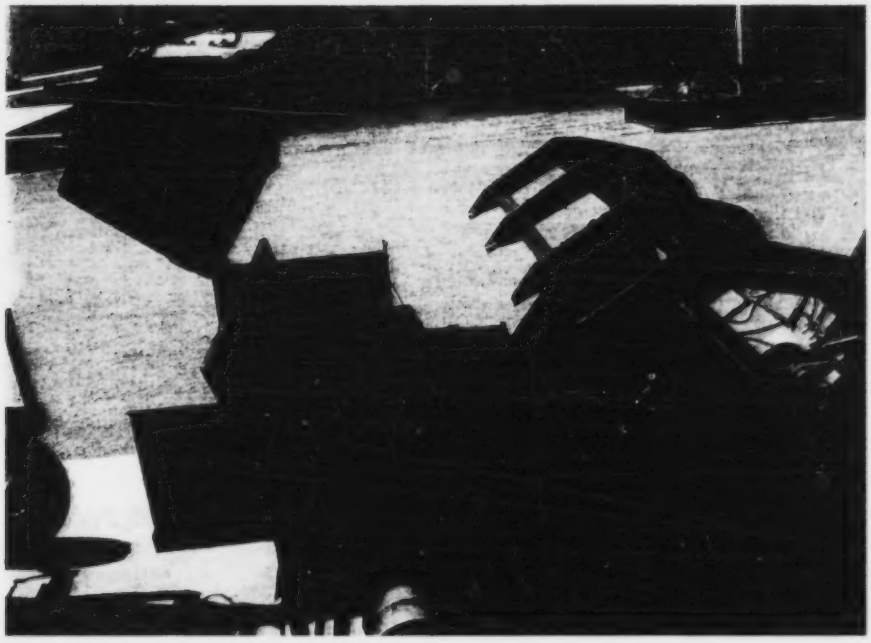

Figure 3. Testing of the Knife Chopper.

5.2 Results

Table 1 and **Table 2** include the properties of the manure samples and the power requirements of the knife and flail processors respectively. **Figure 4** shows one of the manure samples before and after processing by the two units.

Table 1. Initial and Final Manure Properties and Power Requirements for the Knife Chopper.

Sample	Average Moisture Content (%)	Average TS[1] (%)	Bulk Density		Density Change (%)	Power (@ 550 rpm)	
			Initial (kg/m^3)	Final (kg/m^3)		100 Hz [2] (hp)	0.5 Sec Avg (hp)
Composting	44.5	55.5	531.3	471.8	-11.2	6.2	2.6
Fresh	74.3	25.7	875.8	842.1	-3.8	17.3	13.0
With Straw	52.3	47.7	628.7	311.1	-50.5	20.9	12.8

[1] Total solids concentration.

[2] Sampling rate.

Table 2. Initial and Final Manure Properties and Power Requirements for the Flail Chopper.

Sample	Average Moisture Content (%)	Average TS (%)	Bulk Density Initial (kg/m^3)	Bulk Density Final (kg/m^3)	Density Change (%)	Power (@ 700 rpm) 100 Hz (hp)	Power (@ 700 rpm) 0.5 Sec Avg (hp)
Composting	44.5	55.5	294.8	328.7	+11.5	24.2	4.6
Fresh	74.3	25.7	916.9	851.7	-7.1	27.9	15.8
With Straw	52.3	47.7	408.9	347.7	-15.0	19.1	9.4

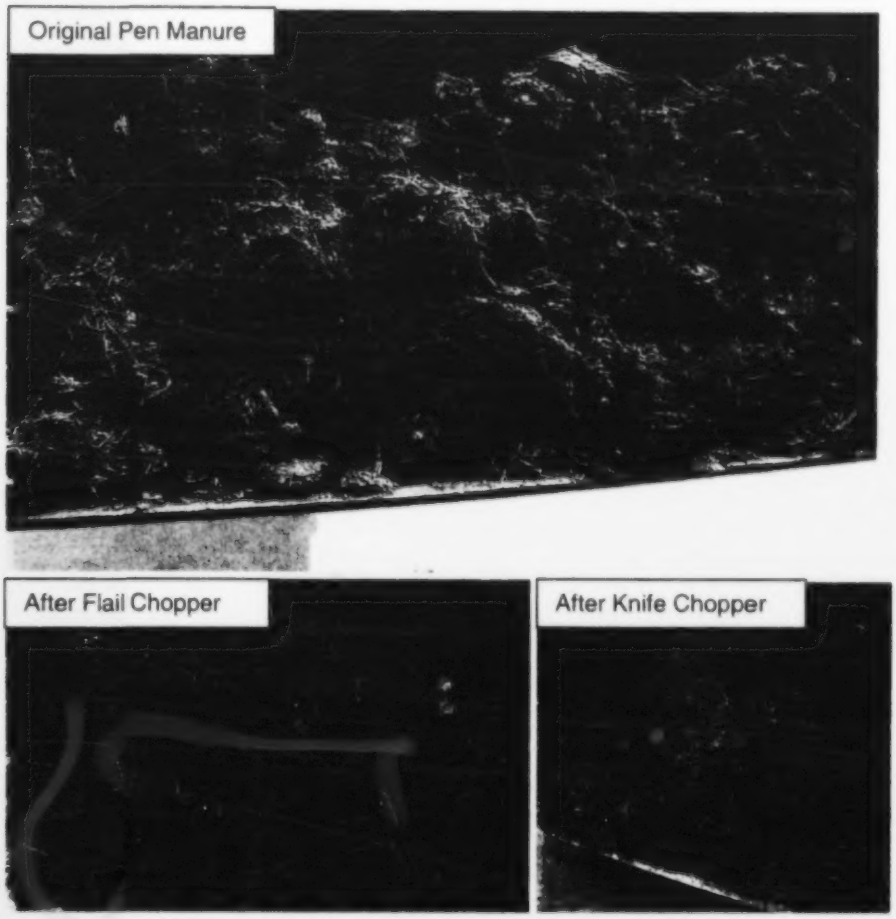

Figure 4. Pen Manure (With Straw) Sample Before and After Processing.

5.3 Conclusions

The main findings were:

- Both processor concepts were capable of handling manure products over a wide range of consistency.
- The particle size was effectively reduced by the processors.
- The products were homogenized by the processors.
- The knife chopper appeared to give a finer product.
- Although the value of the bulk density of solid organic fertilizers is known to be dependent upon the measurement method and variable within the same sample, in most cases manure processing resulted in a decrease in bulk density.
- The power requirements of both units were comparable. It is likely that the performances of both processors will be affected by the operational velocity and a number of geometric parameters. Although it does not appear to be a critical factor, the feeding rate of the processors is likely to influence their performances as well. Further testing is desirable, but it has been proven that manure can be processed with straw choppers or similar devices.

6. Evaluation of the Prototype Land Applicator

The prototype precision land applicator developed at the University of Saskatchewan (**Figure 5**) was evaluated to guide the design of the injection device. That machine has the ability to evenly distribute the product over the entire width of its transverse distribution system (9 ft (2.74 m)). The injection device developed within the scope of the project reported herein will be adapted to the precision land applicator to create an injection-ready, field-scale prototype.

Figure 5. Prototype Precision Land Applicator, Basic Machine for the Development of the Solid Manure Injection Device.

6.1 Assessment of the Uniformity of Distribution and Visual Appreciation of Various Application Rates

Portable scales were used to weigh the spreader (hitch and tires) during field experiments. A first load of feedlot manure with chopped straw from a pen was spread at a speed of 2.0 mph (3.2 km/h). The resulting application rate was 13.1 tons/ac (29.4 t/ha). It should be noted that a typical one-year application rate for beef cattle manure is 8.8 tons/ac (19.7 t/ha).

A second load of the same product was then spread in two steps: one at 1.1 mph (1.8 km/h) and the second at 0.75 mph (1.2 km/h). The resulting application rates were 23.4 tons/ac (52.5 t/ha) and 34.7 tons/ac (77.8 t/ha). The application rates were estimated from the first load and the ratio of travel speed (no actual

weighing). **Figures 6** and **7** illustrate the resulting ground distribution. **Figure 7** shows the increasing application rates (13.1 tons/ac (29.4 t/ha) on the left-hand side, 23.4 tons/ac (52.5 t/ha) in the middle, and 34.7 tons/ac (77.8 t/ha) on the right-hand side). The uniformity of distribution was deemed good with the outside bands being heavier than the middle four bands. It was perceived that fine-tuning the size (and orientation) of the apertures would improve the uniformity of distribution.

A third load of manure (fourth run) was spread. This time, manure with less straw was collected from the same pen. The sample also appeared to contain more water than the previous two. The application rate obtained at 1.1 mph (1.8 km/h) was 40.7 tons/ac (91.2 t/ha).

Figure 6. Assessment of the Uniformity of Product Distribution (Picture Shows an Application Rate of 13.1 tons/ac (29.4 t/ha)).

Figure 7. Various Application Rates Achieved by the Prototype Land Applicator (13.1, 23.4, and 34.7 tons/ac (29.4, 52.5, and 77.8 t/ha)).

6.2 Performance of the Feeding Fingers

Observations made during field experiments involving manure with large clumps carried out in the summer of 2004 led to the addition of feeding fingers on the shaft of the main discharge augers (**Figure 8**). The fingers were installed to avoid having large clumps riding on top of the shafts of the discharge augers without falling into the secondary hopper. The fingers did allow for the clumps to be forced down towards the distribution auger.

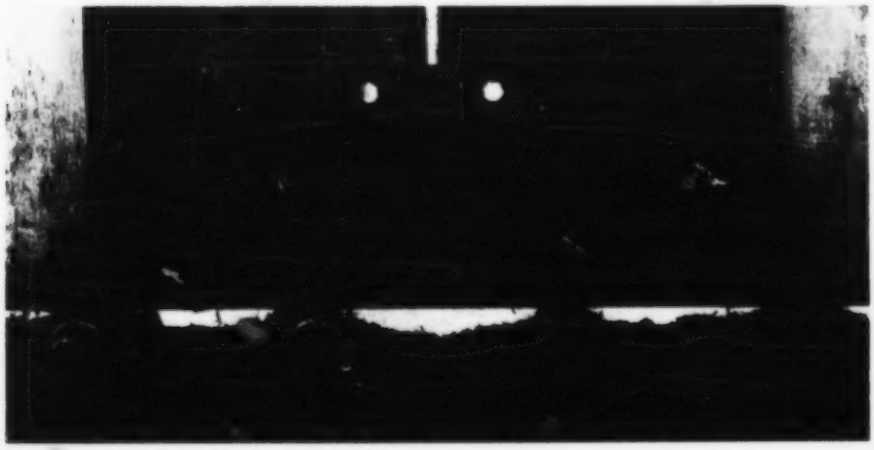

Figure 8. Feeding Fingers on the Discharge Augers.

The field experiments of June 2005 revealed that the fingers could be responsible for an accumulation of manure on top of the discharge augers when the gate was set higher to achieve greater application rates. Selected fingers were removed or shortened on June 7, 2005, (**Figure 9**). The first fingers that were removed were the two that were closest to the flighting and that were observed to cause manure accumulation and compacting between the flighting and the finger. Successive finger shortenings and removals were performed and improvements in flow were observed. Feedlot manure with straw could be spread with gate settings up to 4-6 in (100-150 mm) (*when the gate is at its lowest position there is a distance of approximately 1 in (25 mm) between the bottom of the gate and the top of the auger's flighting; when the gate is set at 4 in (100 mm) there is an additional 4 in (100 mm) of distance between the gate and the top of the augers*).

Based on those observations and with the objective of further improving the flow of manure with straw, only one finger per auger was left and the locations of the fingers were selected as to maximize the size of the flow section. An evaluation of the new finger configuration was carried out on June 23, 2005. It was observed that manure with straw would accumulate even more at the discharge end of the spreader. Practically, only a gate setting of 2 in (50 mm) would be possible with the new finger arrangement. It appears that the former feeding fingers, although reducing the flow section, did force the product to fall into the secondary hopper. The new configuration (1 finger per shaft) did not force the product down and sometimes even lifted the product every cycle increasing the accumulation of manure above the discharge augers. It now appears that manure with straw will not free flow between the auger shafts. It has to be forced down or the flow area has to be further increased or a combination of the two. Shortening the shafts of the four discharge augers (to the end of the troughs) to fully open the transition discharge area was planned for the winter of 2006.

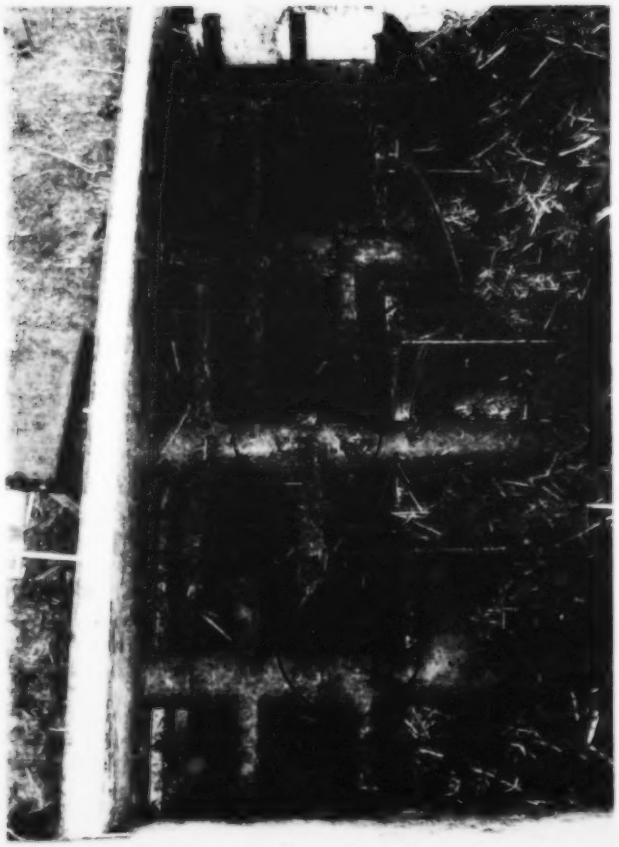

Figure 9. Some Fingers Were Tentatively Removed to Improve the Flow of Manure with Straw.

6.3 High Application Rates

One of the objectives of the preliminary evaluation of the prototype was to obtain the maximum discharge rate that can be handled by the distribution system. To apply 30 tons/ac (67.2 t/ha) at 4 mph (6.4 km/h), the machine would have to output 73 lb/s (33 kg/s) of manure, given the actual application width. This would correspond to approximately a three-year rate.

Two loads of compost were used in trying to reach a discharge rate of 73 lb/s (33 kg/s). The first run was carried out with the gate at the 12 in (305 mm) setting and the tractor running at 1,600 rpm. The resulting discharge rate was 48.5 lb/s (22 kg/s). With the gate at 15 in (381 mm) and the tractor running at 2,240 rpm, a discharge rate of 63.9 lb/s (29 kg/s) was achieved. During this last run, it was observed that approximately 2/3 of the horizontal flow section (finger area) was used. It appears that the discharge rate of 73 lb/s (33 kg/s) is achievable with compost.

6.4 Processed Manure

Feedlot manure with straw taken from a pen was processed using a knife chopper and spread with the prototype land applicator. It was observed that the processed manure flowed much better than the unprocessed product. The gate settings of 2, 4, 6, and 8 in (51, 102, 152, and 203 mm) did not cause accumulation in the finger area. The gate was opened to its highest setting causing an accumulation of manure, but closing down the gate to its lowest position allowed the system to evacuate the product through the discharge auger. With unprocessed manure, an accumulation issue could not be overcome by temporarily closing the gate. It is however evident that the flow area leading to the transition hopper still needs to be increased.

The processed manure had to be stockpiled before loading into the spreader. It also stayed in the spreader for some time before land application. This settling time did not seem to have an adverse effect on the physical properties of the processed manure. Concerns had previously been raised to the effect that leaving the processed manure in the hopper or in a pile would somewhat force the product to go back to its unprocessed state; the issue may still arise with fresh (pasty) manure.

7. Conveying Subsystem of the Injection Device

7.1 Preliminary Calculations and Design Criteria

The conveying subsystem must meet two important criteria: (1) it must be physically flexible enough to be adapted to the prototype land applicator (**Figure 5**), and (2) it must be capable of moving product from its intake to its discharge point at an acceptable rate.

Based on the one-year application rate of a long-term manure application study that PAMI is involved in with the University of Saskatchewan, the machine maximum output, corresponding to a travel speed of 4 mph, can be calculated as:

8.8 tons/ac (19.7 t/ha) x	8.83 ft (2.7 m) x	4 mph (6.4 km/h) =	20.9 lb/s (9.5 kg/s)
Application rate	*Machine width*	*Travel speed*	*Discharge rate*

Agronomic considerations suggest a 12 in (305 mm) row spacing for the injectors. Based on this criterion, the discharge rate at each injector becomes 2.4 lb/s (1.1 kg/s). A spreadsheet was designed to allow for the rapid calculation of the discharge rate per injector based on the application rate, injectors spacing, and travel speed.

7.2 Extrusion

7.2.1 Plunger

A test bench was fabricated to evaluate a plunger-type injection system (**Figure 10**). A number of difficulties were experienced with the plunger-type extruder. Feeding the plunger chamber was perceived as a major obstacle of the system. Also, the pulsating nature of the system and the achievable output rates were deemed inappropriate for a solid manure injection device. Moreover, the plunger could not extrude compost with the available power. The lack of moisture in the product leading to insufficient lubrication has been identified as a potential cause to the problem.

The challenges of feeding the plunger providing lubrication and developing a two-cylinder system to make the flow continuous were prohibitive and the system was ruled out at that point in the project.

Figure 10. Plunger-type Extrusion Device.

7.2.2 Screw-type Extruder

The preliminary assessment of a screw-type extrusion device gave promising results. The first flexible screw conveyor test bench (see Section 7.3) was tested without the flexible conveyor; that is, the hopper was tested with the tapered screw conveyor only (**Figures 11** and **12**). At 250 rpm, the output of the small extruder was 0.29 lb/s (0.13 kg/s) and that rate could be increased to 0.37 lb/s (0.17 kg/s) by increasing the rotational velocity to 400 rpm. The system was tested with a 7.5 ft (2.3 m) section of hose attached at the outlet. The small screw extruder was capable of pushing the product approximately 6 ft (1.8 m) into the hose before powering out. The measured hydraulic power was approximately 2.9 hp (2.2 kW).

Figure 11. Feeding Auger (4.5 in (114 mm) Diameter; 4.5 in (114 mm) Pitch; Tapered to a 3 in (76 mm) diameter) With Flexible Screw Conveyor Removed.

Figure 12. Testing of the Screw-type Extruder. The Flexible Auger was Removed Leaving the Tapered Feeding Auger and 8 in (203 mm) of Steel Pipe at the Discharge.

Besides presenting a power issue, the speed of extrusion of the small screw extruder was insufficient. Based on the results obtained with the small screw extruder, a larger extruder was fabricated. A 10 in (254 mm) diameter screw conveyor was used (**Figure 13**). An extrusion cone was fabricated. The cone brought the diameter from 10 in (254 mm) to 3 in (76 mm) over an 11 in (279 mm) distance (cone angle of 37 degrees). With an open discharge (no tapered section), the system was capable of outputting over 5.6 lb/s (2.5 kg/s). The actual capacity of the auger could not be reached by manually feeding it. The extrusion cone however created plugging problems (**Figure 14**). The system would power out at 10.5 hp (7.8 kW). An increase in power was not deemed an acceptable solution.

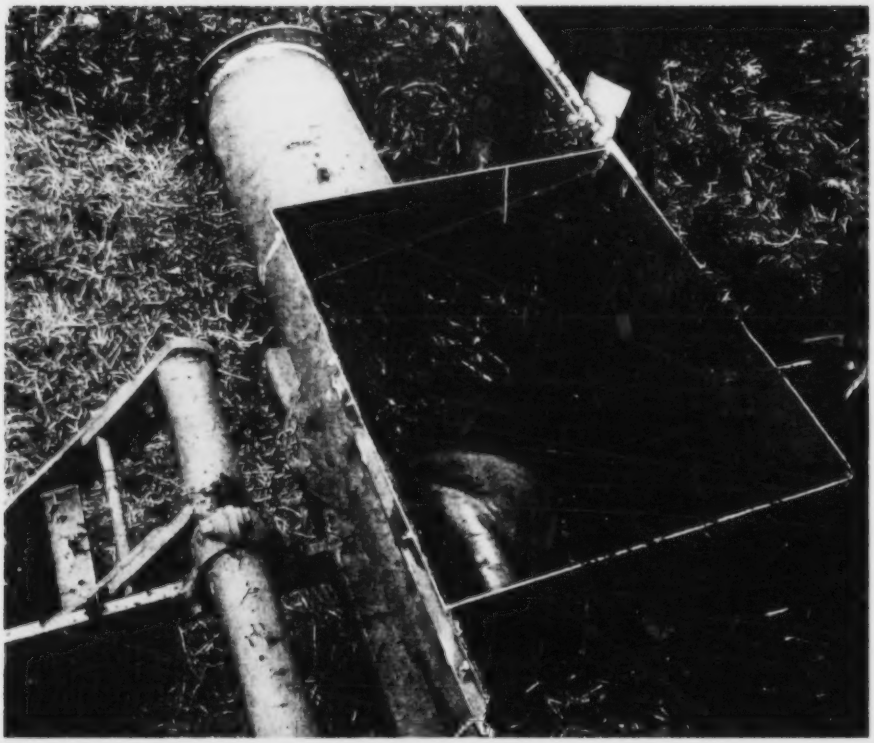

Figure 13. Testing of a Large Screw Extruder.

A triple outlet plate was tested instead to take advantage of the large capacity of the extruder (**Figure 15**). Sections of hose were installed on each outlet nozzle. During field testing, the system could push the product over distances of 4 to 6 ft (1.2 to 1.8 m) into the hoses but powered out. A test was then carried out without the hoses and with a slower feeding of the extruder. This strategy revealed that the system was capable of extruding an amount of product that could potentially surpass the requirements while using approximately 2.3 hp (1.7 kW) of hydraulic power, but that the feeding rate had to be precisely controlled. Also, the friction in the plastic hose increased the resistance beyond the extrusion/pushing capacity of the system. It is important to note that the slow feeding of the extruder with the cone in place still presented plugging issues.

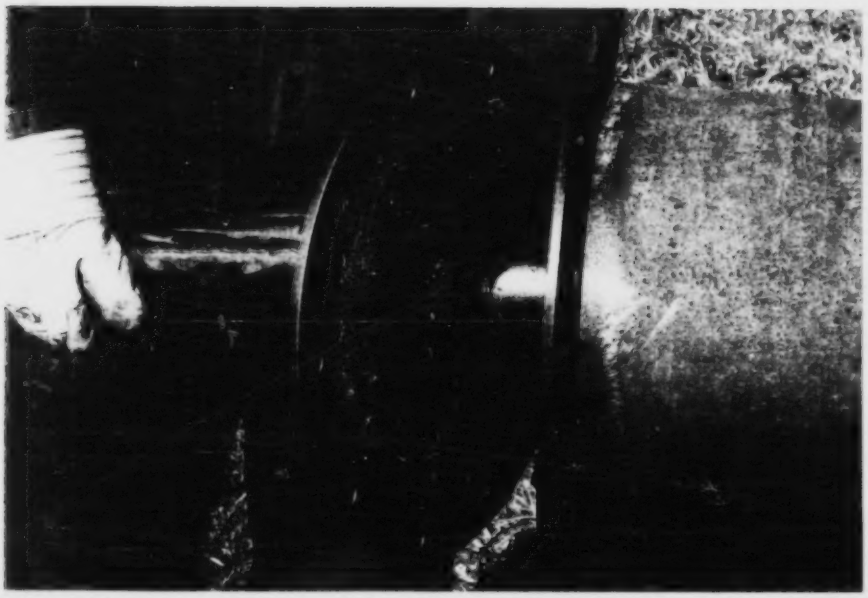

Figure 14. Plugging Problem with the Extrusion Cone on the Large Screw Extruder.

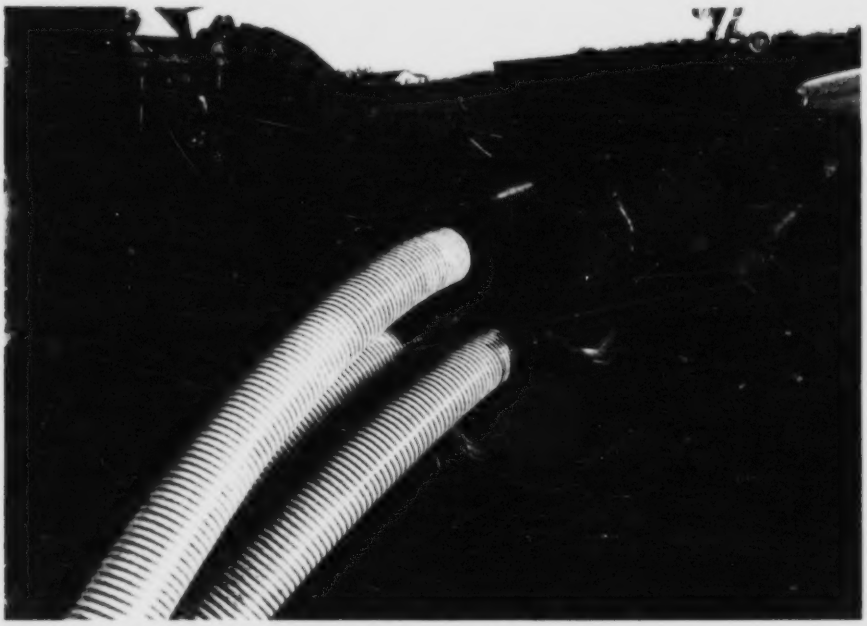

Figure 15. Triple Outlet Plate on Large Extruder.

The investigation of extrusion mechanisms revealed that these systems are sensitive to the feeding rate and that there exists complex relationships between their geometry and other operating parameters. The presence of hoses at the discharge of the extruders created an important increase in the power requirements.

7.3 Flexible Screw Conveyor

The flexible screw conveyors available on the market are basically a steel coil that is used to move granular product inside a flexible pipe or hose. A first test bench was fabricated with a flexible screw conveyor (2.38 in (60 mm) diameter; 2.5 in (64 mm) pitch) directly attached to a driving shaft (**Figure 16**).

Figure 16. Top View of the Flexible Screw Conveyor Test Bench Showing the Flexible Screw Conveyor Directly Attached to the Drive Shaft.

Field testing of the flexible screw conveyor was carried out with beef cattle manure. The flexible screw conveyor was not efficient in feeding into the hose. Beef cattle manure compost could be conveyed, but important bridging problems were encountered when clumps were present in the sample.

The test bench was modified by adding a section of regular screw conveyor (4.5 in (114 mm) diameter) to feed the flexible screw conveyor (**Figure 17**). The flighting of the regular screw conveyor had to be tapered from a diameter of 4.5 in (114 mm) to a diameter of 2.38 in (60 mm).

Figure 17. Section of Regular Screw Conveyor to Feed the Flexible Screw Conveyor.

The 4.5 in (114 mm) screw conveyor, with a 4.5 in (114 mm) pitch, could handle clumps better than the flexible screw conveyor. The capacity tests of this modified system indicated that an output rate of 0.84 lb/s (0.38 kg/s) was achievable when the screw conveyors were operated at 300 rpm. Bridging problems were still occurring over the 4.5 in (114 mm) feeding screw conveyor. To assess the possible output of this feeding system, the flexible screw conveyor was removed and the test bench was tested as an extruder (see Section 7.2.2). The flexible screw conveyor was eventually reattached to the 4.5 in (114 mm) feeding conveyor. To circumvent the bridging problems, the system was force-fed manually. This resulted in the observation of important deformation of the flexible screw conveyor. When the flexible conveyor would come under a certain load, it would compress back into the hose and eventually plug. Force-feeding the system and removing the plastic hose resulted in a maximum rate of 1.2 lb/s (0.54 kg/s) (see **Figure 12** for the flexible screw conveyor test bench). A new flexible conveyor, having a diameter of 2.75 in (69.8 mm) and a pitch of 2.25 in (57.2 mm), was tested. At 250 rpm, the system yielded a discharge rate of 1.4 lb/s (0.64 kg/s). Increasing the velocity to 350 rpm resulted in a discharge rate of 1.6 lb/s (0.73 kg/s). It was concluded that a larger pitch and diameter on the feeding conveyor were needed to facilitate the movement of product from the hopper into the flexible conveyor.

A new test stand was built with a 6.5 in (165.1 mm) auger (standard pitch) tapered down to the 2.75 in (69.8 mm) flexible screw conveyor (**Figure 18**). With a 14 ft (4.3 m) section of plastic hose on the flexible screw, conveying problems were observed. The new feeding screw conveyor was overwhelming the flexible conveyor. A test carried out at 350 rpm resulted in a discharge rate of 1.3 lb/s (0.59 kg/s). Increasing the rotational velocity of the augers to 500 rpm resulted in a 2.0 lb/s (0.91 kg/s) discharge rate. Removing the plastic hose resulted in a 3.0 lb/s (1.4 kg/s) rate at 350 rpm indicating that the capacity of the feeding conveyor was too large for that of the flexible conveyor. The system was also

tested with beef cattle manure compost. The compost could not be fed as aggressively in the hopper as it would compact into the tapered (cone) section leading to the flexible conveyor. It was easier to feed the 6.5 in (165.1 mm) auger as to overwhelm the flexible conveyor with compost as compared to manure. In addition to presenting a different compaction behaviour, the lower moisture content of the compost could not provide lubrication to facilitate the movement of product inside the plastic hose. Running the system in forward and reverse allowed clearing the compost plug, but deformation of the flexible conveyor was observed.

Several tests were carried out including a series of tests with a 13 ft (4 m) section of steel pipe. The metal pipe was investigated, as it could be possible to have in the final design, straight sections that could benefit from the potential increase in flow ability. The use of a steel pipe did not improve the performance of the system. In fact, the flow through the steel pipe was observed to create more backfilling problems at the outlet of the hopper (inlet of the pipe). Removing the steel pipe resulted in discharge rates comparable with what had been measured in previous tests, indicating that the steel pipe was not a viable option. Also, while the product properties had been fairly constant for all the previous experiments, the system revealed to be sensitive to a dryer product containing more straw. Plugging problems were encountered with dryer product. To circumvent the problem, a batch of manure was processed with the prototype precision land applicator. Without the hose and at a velocity of 350 rpm, a rate of 2.5 lb/s (1.1 kg/s) was reached. A subsequent plugging resulted in the flexible screw conveyor buckling.

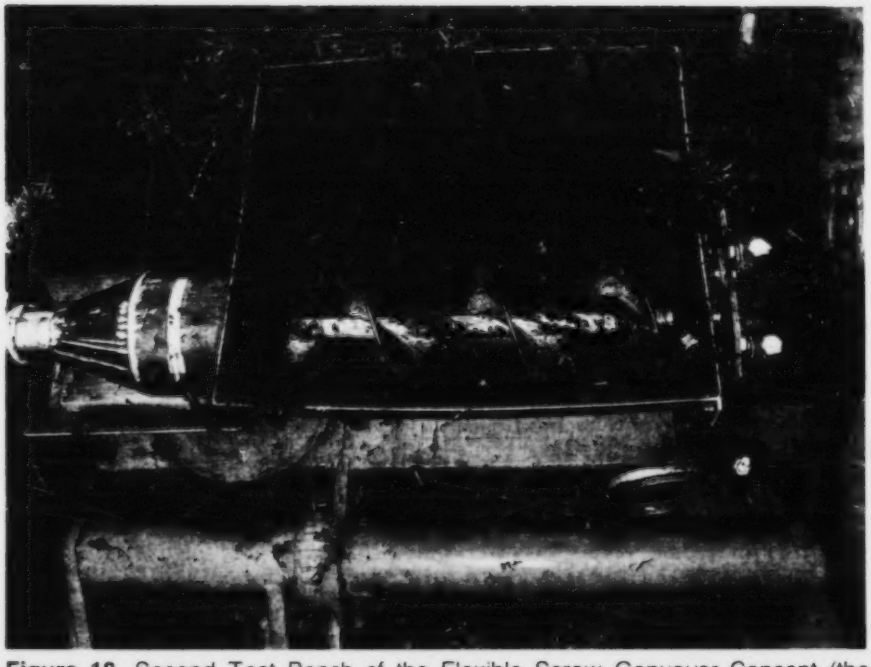

Figure 18. Second Test Bench of the Flexible Screw Conveyor Concept (the 6.5 in. Feeding Auger is Shown With the 3 in (inside diameter) Hose Attached at the Discharge).

All these tests suggested that the system had good potential but needed to be upsized. A larger diameter flexible screw conveyor was installed on the test bench (3.56 in (90.4 mm)). When an initial test of the new flexible screw conveyor revealed an unsatisfactory amount of deformation of the conveyor under load, it was decided that it should be made stiffer by welding together two flexible screw conveyors. A test was carried out at 490 rpm with unprocessed beef cattle manure. The steady feedrate resulted in a discharge rate of 2.4 lb/s (1.1 kg/s) and a minimal amount of compression of the flexible conveyor. The conveyor was tripled up to investigate the benefits of even higher stiffness. The results indicated that no increase in discharge rate could be obtained with the tripled conveyor. Moreover, the stiffer screw conveyor required more power and even powered out during testing.

The double flexible screw appeared to be the best system among all the variations put to the test. An additional series of tests was carried out to compare the effect of product preprocessing on the achievable discharge rate. The moisture content of manure samples processed by the prototype land applicator and by the knife chopper was measured. The average moisture content for the product that had been through the prototype land applicator was 70% (on a wet mass basis) while it reached 74% for the sample processed with the knife chopper. Both samples were from the same source and, based on the moisture content measurements, could be considered to be the same product. With the

double flexible screw conveyor operated at 490 rpm, the system was capable of discharging 3.7 lb/s (1.7 kg/s) of manure preprocessed by a knife chopper (see Section 5). The power requirement during the test was approximately 7.6 hp (5.7 kW) (the power requirements under no load was approximately 5 hp (3.7 kW)). With manure preprocessed by the prototype land applicator and the system operated at 490 rpm, a discharge rate of 2.6 lb/s (1.2 kg/s) was achieved using approximately 8.1 hp (6.0 kW). Experiments showed that starting the double flexible screw conveyor under load is likely to result in plugging problems. A long test (6 minutes) was successfully carried out at a steady manual feedrate to assess the capacity of the system to run at a steady state. The system appears to be capable of meeting the requirement of a 1-year application rate at 4 mph (6.4 km/h) (2.4 lb/s (1.1 kg/s)). It would however be desirable to operate the system at about 75% of its capacity. It should be noted that reducing the travel speed to 3 mph (4.8 km/h) means that the injector target discharge rate becomes 1.8 lb/s (0.8 kg/s). Also, the application rate of 8.8 tons/ac (19.7 t/ha) used to set the design criteria does not take into account the reduction in rate that could result from solid manure injection due to potentially more efficient availability of the nutrients. It should also be noted that while theoretically the discharge rate of a screw conveyor can be increased by increasing its rotational velocity, it was deemed that 500 rpm was a practical limit for the systems tested.

Another concept of flexible screw conveyor was investigated. Instead of using a commercial coil-type conveyor, sections of regular screw conveyor flighting were attached to a steel cable (**Figure 19**). Numerous field tests were carried out to evaluate the capacity of the cable-auger. A summary of the testing history of the flexible screw conveyor concept is included in **Table 3**. All the capacity tests involved manual feeding. When several increasing discharge rates are presented for the same product at the same rotational velocity, it indicates that the manual feedrate was increased to achieve the maximum possible discharge rate. **Table 4** presents the power requirements of the cable-auger under different operating parameters. The new flexible screw conveyor concept gave the highest rates (the maximum achieved rate was 4.2 lb/s (1.9 kg/s)). The conveyor was pushed to its limit and eventually broke. It was observed that the cable had failed due to a high torsion load. Two different version of the cable-auger were tested. The first version had gauge 11 (0.120 in (3.0 mm) thickness) flighting over the entire length of the conveyor while the second version presented a 5 ft (1.5 m) section of heavier flighting at the feeding end of the conveyor (gauge 7; 0.179 in (4.5 mm)). Both were tested to failure, and it was observed that the failure occurred close to the inlet of the flexible conveyor for the first version and at the transition between gauge 7 and gauge 11 flighting for the second version (**Figure 20**). The heavier flighting provided added strength but was much stiffer.

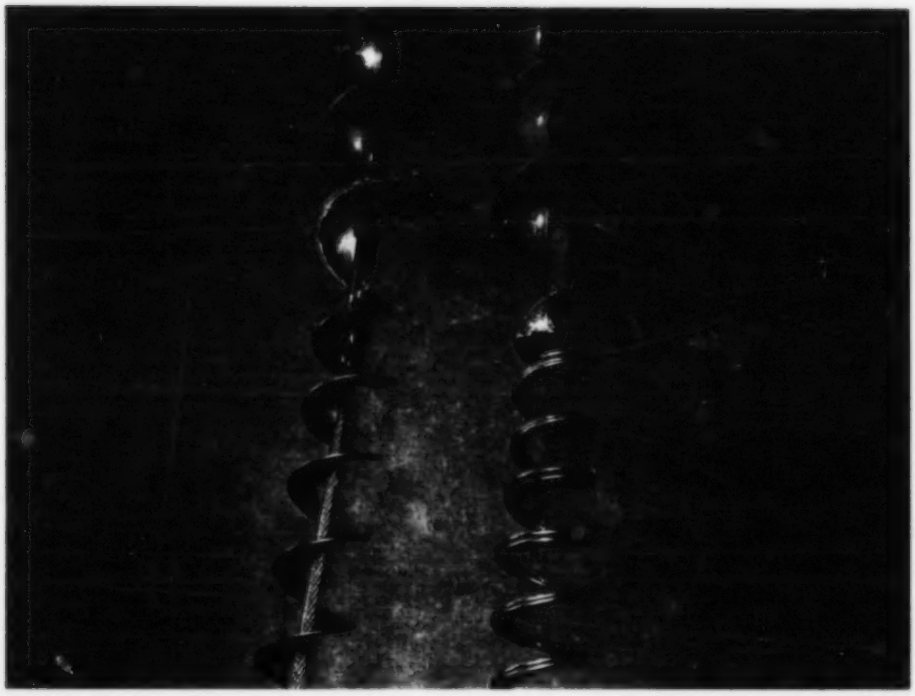

Figure 19. Two Flexible Screw Conveyor Concepts: the Cable-Auger and the Coil-Type Auger.

Figure 20. Failure of the Cable-Auger.

Table 3. Testing History of the Flexible Conveyor Concept.

Description		Feeding conveyor		Flexible conveyor		Rotational velocity	Product	Discharge rate achieved [1]
		Diameter (in)	Pitch (in)	Diameter (in)	Pitch (in)	(rpm)		(lb/s)
Initial test bench – 2.38 in. flex all the way	with hose[2]	2.38 flex	2.5	2.38	2.5	243	compost & manure	bridging; inefficient feeding
Initial test bench - 4.5 in. feeding 2.38 in. flex	no hose	4.5	4.5			200	compost	0.4
						300	compost	0.8
							manure	bridging
						250	manure (force-fed)	1.2
Initial test bench – 4.5 in. feeding 2.75 in. flex	with hose			2.75	2.5	250	manure (force-fed)	1.2
								1.3
						350		1.6
Second test bench – 6.63 in. feeding 2.75 in. flex	with hose	6.63	6.75	2.75	2.5	350	wet manure (fed fast)	1.3
							dry manure (fed fast)	power out
	no hose						manure (over-fed)	3.0
	with hose					500	manure (fed fast)	2.0
	steel tube						compost (fed fast)	plugged
							manure	backflowing
	with hose					350	spreader-processed manure	2.5
	steel tube							not flowing well through tapered section
	with hose							plugged and broke
Second test bench – 6.63 in. feeding double 3.56 in. flex	with hose	6.63	6.75	3.56	2.63	350	manure	1.6
						490		2.4
Second test bench – 6.63 in. feeding triple 3.56 in. flex						495	dry manure	1.2
							manure	power out
Second test bench – 6.63 in. feeding double 3.56 in. flex						490	preloaded chopped manure [3]	3.7
							chopped manure (fast fed)	2.9
								3.3
							preloaded spreader-processed manure	plugged
							spreader-processed manure (fast fed)	1.9
								2.5
								2.6
Second test bench – 6.63 in. feeding 3.5 in. auger with cable core	with hose	6.63	6.75	3.5	3.5	510	spreader-processed manure	2.4
							spreader-processed manure (fast fed)	4.2
						490	spreader-processed manure	2.8
						354		2.3
						354	spreader-processed manure (fast fed)	3.2
						503		3.5
								3.8
						503	compost (dry; slow feeding)	1.9

[1] For reference, a typical one-year application rate for beef cattle manure assuming a spacing of 12 in. and a speed of 4 mph is 2.4 lb/s.
[2] The hose was a flexible air seeder hose; when a pipe or a hose was used, its length varied from 12 to 15 ft.
[3] "Preloaded" means that the hose and the conveyor were filled with manure prior to the test (to cancel the effect of manual feeding).

Table 4. Power Requirements of the Cable-Auger.

Rotational velocity (rpm)	Hose bends	Product	Discharge rate (lb/s (kg/s))	Power (hp (kW))
350	straight	none	0	2.2 - 2.3 (1.6 – 1.7)
	90 deg. bend (approx. radius of 4 ft)			2.6 (1.9)
497	Straight			5.0 (3.7)
	90 deg. bend (approx. radius of 4 ft)			5.3 (4.0)
490	gentle bends	spreader-processed feedlot manure	2.8 (1.3)	8.1 (6.0)
354			2.4 (1.1)	3.9 (2.9)
			2.3 (1.0)	4.7 (3.5)
			3.2 (1.5)	5.5 – 7.8 (4.1 – 5.8)
503			3.5 (1.6)	8.2 (6.1)
			3.8 (1.7)	9.2 (6.9)
		compost	1.9 (0.9)	6.8 (5.1)

7.4 Summary of the Results Obtained With the Various Conveying Systems

Several means of conveying the product from the distribution system to the trench in the ground were investigated. Some general observations can be highlighted regarding the performances of the various systems that were put to the test. All the systems tested (extruders and flexible conveyors) were affected by the moisture content of the product. Compost, with sand-like properties, created major problem with extrusion devices. Plugging and powering out were observed when attempting to extrude compost. It is believed that the low moisture content of the product did not allow for sufficient lubrication to be generated, thus increasing the power required to extrude the product. The flexible screw conveyors were less sensitive to compost. However, the tapered section of the feeding conveyor could plug if compost was fed at too high a rate. The flexible screw conveyors were observed to be affected by samples of manure containing a large proportion of straw. The amount of straw was assumed to increase friction as well as the power required to force the straw into the tapered section and eventually into the flexible conveyor.

The feeding conveyor that is used to bring the product to the flexible conveyor was incrementally sized up as the system was developed. It appears that the pitch and the diameter of that feeding conveyor must be of a minimal size to accommodate the larger aggregates that are present in the products. There is a relationship between the

section is also a factor that influences the performance of the system. A viable compromise has been reached, but the optimization of the feeding system of the flexible conveyor is a challenge that remains to be addressed.

Raw manure along with manure that had been subjected to two levels of processing was used during the experiments. The manure flowed through the prototype land applicator (see Section 6) where the discharge screw conveyors and the distribution conveyor processed the product to some extent. A more aggressive processing was also achieved by using a straw chopper (see Section 5). Observations made during the testing of the flexible conveyor system led to the conclusion that processing increased the flow ability of the product. The homogenization effect and the breaking up of the hard clumps made the product flow easier, especially in the tapered section of the feeding conveyor.

8. Soil-Opening Subsystem of the Injection Device

The function of this subsystem is to create in the ground a void of sufficient volume to accommodate a practical application rate at a reasonable travel speed. The first soil opener that was investigated is the disc. A Bourgault liquid manure injection disc (24 in (609 mm) diameter; 0.25 in (6.4 mm) thickness) was first mounted on a toolbar and tested in the field. At the 5 degrees factory setting for the angle of the disc with the direction of travel in a horizontal plane (toe-in angle), the disc opened a trench 5 in (127 mm) deep with a 1 in (25.4 mm) width at the bottom. A wider furrow was required to accommodate the hose of the injection system. The disc angle was increased to 10 degrees resulting in a 4 in (101.6 mm) wide trench at a 5 in (127 mm) depth. The opener with an increased toe-in angle is illustrated in **Figure 21.**

Figure 21. Disc Opener.

The closing wheel was modified to reflect the changes made to the opener. Its diameter was increased from 15 to 18 in (381 to 457 mm) to accommodate the larger volume of soil displaced by the coulter disc at the increased angle. Modifications were also brought to the position of the closing wheel and its angle. The closing wheel was moved 2 in (50.8 mm) further to the left on the member linking it to the spindle, and 2.5 in (63.5 mm) further back on its support member. The toe-out angle was increased by 11 degrees (from 4 to 15 degrees) but no changes were made to the camber angle. The closing wheel gave satisfactory results in a variety of field conditions - pea stubble, barley chemical fallow, and summerfallow (**Figure 22**). Further adjustment of the operating

parameters of the closing wheel could potentially increase its performance. The addition of a packing wheel has also been suggested as a means of improving the soil disturbance level visible after the passage of the injector.

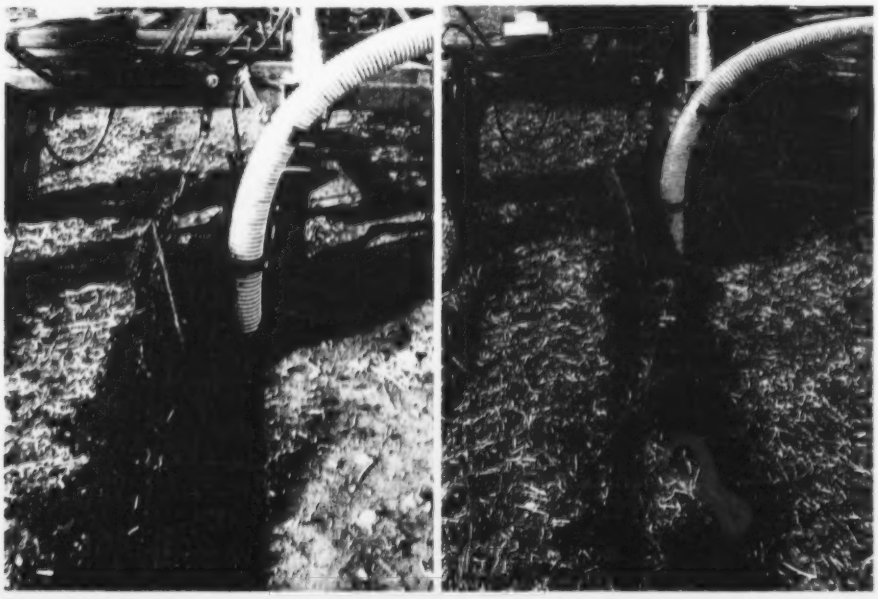

Figure 22. Performance of the Closing Wheel in Various Field Conditions.

An alternate soil-opening subsystem was also investigated. The desired action was to lift the soil, deposit the manure (with the conveying subsystem), and drop the soil back. A mouldboard plough was used to study that principle. A single plough share was mounted on a toolbar and field tested. While the plough had the ability to open up a trench of sufficient volume, the resulting level of soil disturbance was deemed unacceptable. Several modified versions of the plough were field tested with similar results (**Figure 23**).

Figure 23. Field Testing of a Modified Mouldboard Plough.

9. Complete Injection Device

The complete injection device (flexible screw conveyor combined with disc opener) was field tested. The system was capable of effectively depositing the manure in the trench. During the field testing of the complete injection device, the system was fed manually making it hard to achieve a steady feedrate as the machine is moving. The numerous stationary tests carried out to assess the flexible conveyor system proved that it could discharge a steady amount of manure provided that the feeding rate remained relatively constant.

10. Recommendations for Final Design

The results included in this report demonstrated that the screw conveyor with a cable center was the most efficient system to transport the manure from the transverse distribution conveyor to under the soil surface. The discharge rates achieved with that system were the greatest while maintaining power requirements equal to or lower than the double flexible (coil) screw conveyor. It appears that the power requirements of the system under no load are relatively important. It was demonstrated (**Table 4**) that the rotational velocity of the screw conveyor has an influence on the power requirements. Further testing of the system will allow for the determination of the optimal rotational velocity. While the tests carried out at 350 rpm resulted in lower power requirements, the system showed signs of being close to its limit when attempting to achieve the target discharge rate. The optimal rotational velocity should be in the 350 to 500 rpm range.

The center cable of the auger has failed twice due to the torsion load. It is recommended to attempt strengthening the system by using metal sleeves over the cable. These sleeves could be soldered on the cable over their entire circumference for added strength. The sleeves would also provide an improved welding surface for the flighting. There are also other designs of cables, which may be more suitable than the one tested. Depending on the bend patterns the hoses will have to assume in the final design, heavier flighting (see Section 7.3) should be considered where the bending radius allows. Strengthening the flexible conveyor should permit starting the system under load, an action that was observed to create plugging (and eventually breaking) problems during field testing.

Hoses made of transparent plastic were used to facilitate the observation of the flow during field testing. However, other types of hoses should be investigated as they may improve the performance of the system. The desirable features of the hose include easiness of bending and low friction coefficient.

The presence of foreign objects in the manure that could potentially reach the injectors is a concern. A pressure relief system on each unit could be designed to allow the feeding conveyor to evacuate the object. For example, a spring loaded cone (tapered section of the pipe on the hopper of each injector) could be used as a pressure relief system.

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